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Polygeneration Solar Air Drying

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Abstract

Over 85% of industrial dryers are of the convective type with hot air or direct flue gases as the drying medium which involves removal of water. In this study, the performance of a solar air heater with the recovery of the absorbed heat by the metallic concentrator sheet itself besides it's normal heat accumulation in the receiver at the focus of the concentrator for generating drying air at a low to medium temperature range is discussed. The system performance through thermal analysis & the performance of a model achieving the required temperature range is investigated in this study.

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Keywords: Dryer; Polygeneration; Moisture ; Equilibrium ; Humidity;

1. Introduction

A low cost thin metallic sheet concentrator having moderate reflectance of around 70% will concentrate solar irradiation at the focus simultaneously with some absorbed solar irradiative heat due to it's conductive property. If both accumulations are shared in drying purposes at different temperature ranges, the mass flow rate will increase giving out higher rate of drying effect at a higher temperature range than a flat plate collector of equal area projected on the ground. Earlier, increased surface area through corrugation of the absorber or use of wire mesh by H.P.Garg et. el[1], heat transfer enhancement through turbulence by Evan,D.L et.el[2], use of fins as barriers for boundary layer breaking & collector dead zone reduction by Esan et el.[3] were investigated for better performance of the collector. Hollands(1981), Arnold (1977, 1978) et. el. [4,5] proposed for specularly reflecting honeycomb for radiation trap & convection suppression to minimize the radiative loss. Bolin at el. [6] found that higher rate of drying can be achieved either by temperature rise & higher rate of convective heat transfer or minimization of moisture barriers like dense hydrophobic skin layers or long water migration paths of the products to be dried. Developments in solar drying of agricultural products have been studied by several investigators

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inclusive of Jayaraman and Das Gupta [7], T.A. Lawland et el.[8], J.V. Carbonell et el.[9].In a direct method of solar air drying, air is heated in a solar collector which is ducted to the drying chamber to dehydrate the product. The moisture of the agricultural food product in discussion gets evaporated from the surface through heat transfer developing a temperature gradient followed by a mass transfer of moisture from the inner part of the feed to continue the process. This moisture migration through diffusion due to the a vapor–pressure gradient, capillary flow & feed shrinkage pressure can be enhanced though optimum supply of hot air of regulated temperature range determined by the residence time period of drying & it's relative humidity. The difference in psychometric properties i.e. partial pressure of water vapor in the air and the partial pressure of the moisture in the product is the driving force for drying. The conventional design of a solar thermal system requires investigation on the system boundary conditions, analysis of process characteristic, heat distribution network analysis, potential analysis for system optimization with energy efficiency measures. This should be followed by system simulations varying the size of the collector field, the collector type and the storage volume, the type of the solar thermal system, the supported processes etc. In this study, the heat generation at the focal point as well as absorbed heat recovered from the concentrator itself has been investigated through the performance of a bench model as referred at Fig.1.

Nomenclature

AH	Auxiliary Heating facility
A	Applications
Ca	specific heat of the drying air [J/kg-K]
C_v	specific heat of the vapour from the product [J/kg-K]
C_p	specific heat of the product [J/kg-K]
C_w	specific heat of water [J/kg-K]
C_w	specific heat of water [J/kg-K]
d	width of the individual gaps between the trays in the dryer [m]
F	Blowers
G_d	specific mass flow rate of the drying air [kg/s-m2]
$h_{c,con\text{-}ad}$	convective heat transfer coefficient between the product and the drying air [W/m2-K]
hc, p-a	convective heat transfer coefficient between the product and the drying air [W/m2-K]
h_{fg}	latent heat of vaporization [J/kg]
I_e	effective solar irradiative heat arriving at the concentrator surface (W/m^2)
m	mass flow rate(kg/s)
$\acute{m}_2$	specific mass flow rate of the drying hot air in the drying cabinet [kg/s-m^2]
m1	mass flow rate of the air from the polygeneration system[kg/s]
m2	mass flow rate of the air at the outlet of the drying cabinet[kg/s]
m3	mass flow rate of the air entering the drying cabinet[kg/s]
M_p	moisture of the product at time t [kgwater/kgsolid]

Nomenclature

M_i	initial moisture content [kgwater/kgsolid]
Me `	equilibrium moisture content [kgwater/ kgsolid]
P	Pumps
q'_{ha}	rate of heat carried away by the air from the space in the system above & below the concentrator bounded by the glass cover & the rear insulator cover respectively (J/kg s)
R	respective thermal resistances due to the radiative &convective heat transfer coefficient$(J/Kg.K)^{-1}$
S	Heat Storage
T_{amb}	ambient temperature (K)
T_{cov}	cover glazing temperature(K)
T_a	air temperature in the system above & below the concentrator bounded by the glass cover & the rear insulator cover respectively equal to temperature(T_{ad})of the drying air (K)
T_{con}	concentrator surface temperature (K)
T_{ins}	temperature of the insulating enclosure(K)
T_{ad}	temperature of the drying air [K]
T_p	temperature of the product [K]
t	drying time [s]
x1	humidity ratio of the drying air [-]
x1	humidity ratio of the drying air [-]
X_r	relative humidity of the air [%]
ρ_p	density of product [kg/m3]

1.1 Thermal analysis

In the proposed bench model, concentrator is made up of thin sheet of low cost stainless steel of 70% reflectance (approx) such that the focal point falls in the aperture plane of the dish concentrator having a aperture diameter of 1040 mm. The rear side is insulated, maintaining the requisite space for hot air bounded by the rear surface of the concentrator & the insulating cover as referred in Fig.1 .The equivalent thermal circuit diagrams at Fig.2 has been analyzed & the heat balance equations will be, for the single cover at temperature T_{cov} , $(1/R_1+1/R_2)(T_{cov} - T_{amb}) + (1/R_3 + 1/R_4)(T_{cov} - T_a) = 0$ (i)

For the volume of air at T_a in contact with the concentrator surface at the same temperature of T_{con}, above & below the concentrator bounded by the glass cover & the rear insulator cover respectively,

$$(1/R_3 + 1/R_4)(T_a - T_{cov}) + (1/R_5 + 1/R_6)(T_a - T_{ins}) + q_{ha} = I_e \quad \text{(ii)}$$

For rear insulator enclosure at temperature T_{ins},

$$(1/R_5 + 1/R_6)(T_{ins} - T_a) + (1/R_7 + 1/R_8)(T_{ins} - T_{amb}) = 0 \quad \text{(iii)}$$

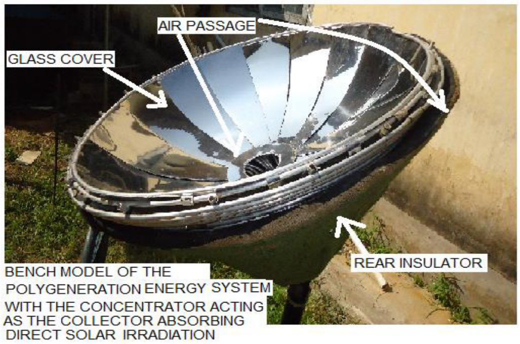

Fig. 1. Bench Model

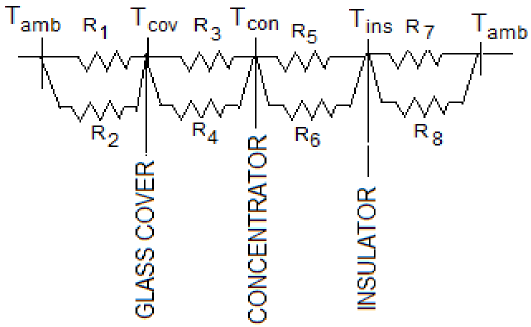

Fig. 2. Simplified Thermal Circuit of the Model

On substitution & rearrangement an expression for total heat recovered only from the absorbed direct solar irradiation will be, $Output = q'_{ha} = I_e - U_L.(A.T_a - B.T_{amb})$

$$A = \left[\frac{1+\left(\frac{2}{R_3}+\frac{2}{R_4}\right)}{(1/R_1+1/R_2)\}}\right]\left[\frac{(1/R_5+1/R_6)}{(1/R_7+1/R_8)+1}\right] - [(1/R_5+1/R_6)(1/R_1+1/R_2+1/R_3+1/R_4)]$$

$$B = [\{(1/R_5+1/R_6+2/R_7+2/R_8)\} - \{(1/R_1+1/R_2)(1/R_5+1/R_6+1/R_7+1/R_8)\}]$$

U_L = Overall loss coefficient of the System $= \dfrac{(R_1\, R_2\, R_3\, R_4\, R_5\, R_6\, R_7\, R_8)}{\left[\frac{1+(R3+R4)}{\left(\frac{1}{R1}+\frac{1}{R2}\right)}\right][\{\left(\frac{1}{R5}+\frac{1}{R6}+\frac{1}{R7}+\frac{1}{R8}\right)(R_1+R_2)\}]}$

1.2 Experimental results

The bench model at Fig.1 took the average temperature readings (^{0}C) in the month of May'2014 at Guwahati, India (Latitude = 26.1838° N & Altitude = 91.7633 E) using two digital thermometers (TESTO, Germany make) simultaneously for the concentrator surface plate as well as the receiver at the focal point of the concentrator with the instant respective ambient temperature as stated in the Fig.3.

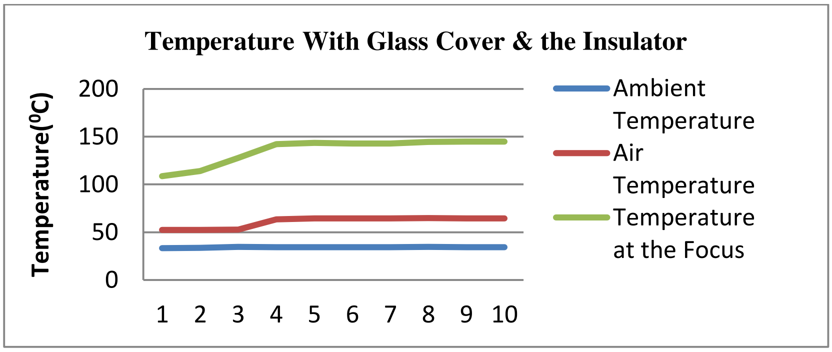

Fig. 3.

At a maximum temperature range of 64^{0}C, drying heat can be supplied to the 40% of food items enlisted in Table 1. & the rest items can be processed by the heat from the receiver at the focal point of the concentrator achieving a maximum of 144^{0}C at which further processing like pre & post drying processes, washing etc can also be done by hot water. Higher is the temperature range, higher will be the mass flow rate of the drying air with the requisite temperature range.

A simple model using Matlab was simulated for the temperature raise only for the recovered heat due to the conductive property of the concentrator for the proposed polygeneration system for the time rate of temperature profile using some arbitrary values for the ambient temperature, insulator temperature, solar irradiation as the independent input variables & the hot air temperature as the dependent variable, all are as the time function referred in Fig. 4. & Fig. 5. The simulated profile has some approximation with that of the bench model readings. Heat recovered at the focus will be at a much higher rate.

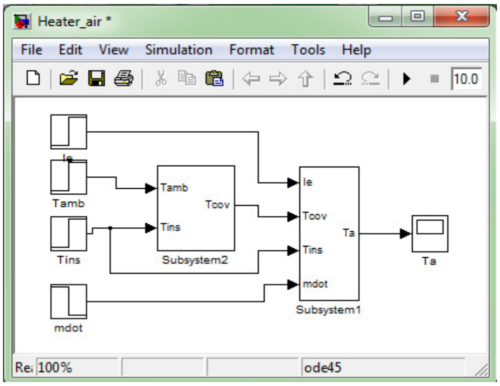

Fig. 4. Block diagram for the air temperature

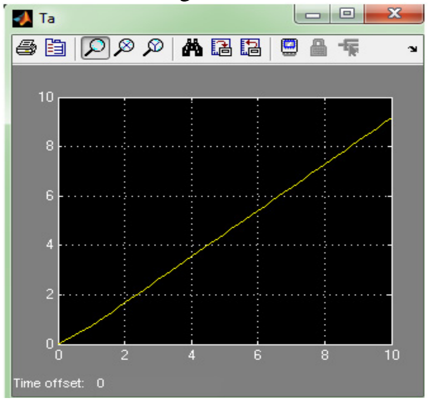

Fig. 5. Simulation of the hot air temperature profile

The temperature range achieved, can serve the purpose of a direct solar air dryer as shown in Fig. 6. This temperature range can be speculated as conducive for drying of a number of agricultural food products enlisted at Table. I. , showing individual temperature range with possible range of moisture removal [10] .

Table. I.[10]

Drying Items	Drying Temperature(^{0}C) 30 50 70 90	Initial Moisture Percent	Final Moisture Percent	Drying Items	Drying Temperature(^{0}C) 30 50 70 90	Initial Moisture Percent	Final Moisture Percent
Bananas		80%	15%	Medicinal		85%	11%
Barley		20%	13%	Oats		25%	13%
Beets		85%	14%	Onions		85%	8%
Cardamom		80%	10%	Peanuts		50%	13%
Cassava		62%	17%	Pepper		80%	10%
Chillies		90%	20%	Potato		85%	14%
Coffee seeds		65%	11%	Pyrethrum		70%	13%
Copra		75%	5%	Rice		25%	12%
Corn		32%	13%	Rye		20%	13%
Cotton		35%	7%	Sorghum		35%	13%
French beans		70%	5%	Soybeans		25%	11%
Garlic		80%	4%	Spinach leaves		80%	10%
Grapes		78%	18%	Sweet potato		75%	7%
Green forages		90%	14%	Tea		75%	5%
Hay		60%	16%	Virgin Tobacco		85%	12%
Longan		75%	20%	Wheat		20%	14%

2.0 Formulation of the model used for drying unit:

The ambient air is driven by a fan passes through the heat recovery section of the system as envisaged through an option as in Figure 4 for stand alone or multiple utilities.
The mass balance equation gives m2 = m1 + m3
The change in enthalpy of the drying air in the drying cabinet is equal to the convective heat transfer to the product, the glass cover and the concentrator acting as the absorber.
Energy balance of the drying air,

$$d\,\acute{m}_3\,(C_a + x\,C_v)\,\frac{\delta T_{ad}}{\delta x} = h_{c,con\text{-}ad}(T_p\text{-}T_{ad})$$

Change in enthalpy of the product is the difference between the convective heat transfer to the product & the heat supplied to evaporate the moisture. Energy balance of the product inside the dryer,

$$\rho_p(Cp + M\,Cw)\,\frac{\delta T_p}{\delta t} = [h_{fg} + Cw((T_p\text{-}T_{ad})]d\,G_d\,\frac{\delta x_1}{\delta x} + hc,\,p\text{-}a(T_{ad} - T_p)$$

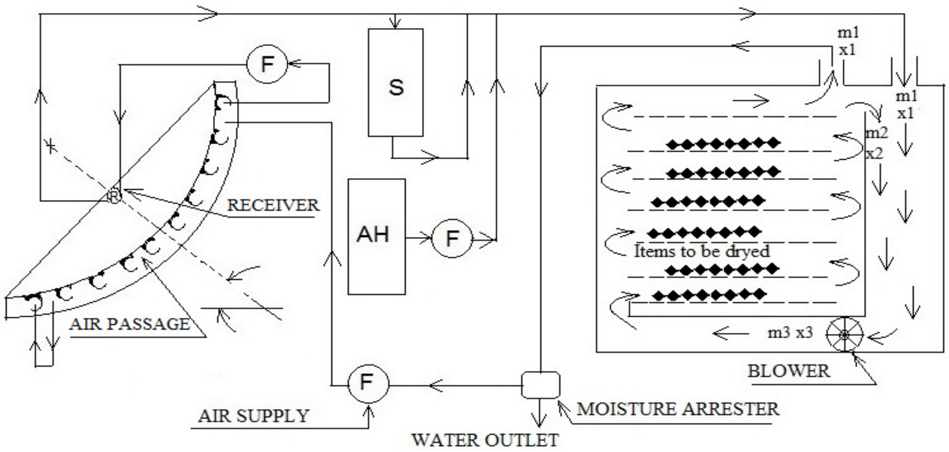

Fig. 6. The proposed system supplying drying air to the dryer unit as the application

Moisture balance states that the moisture gain by the air is equal to the moisture loss by the product. Moisture Balance of the air is

$$d\,G_d\,\frac{\delta x_1}{\delta x} = -\rho_p\frac{\delta M}{\delta t}$$

The moisture content of the product can be expressed by an appropriate thin layer equation. Moisture balance of the product to be dried will be

$$[M_p - Me] / [M_i - Me] = f\,(X_r\,, T_{ad}\,, t)$$

On finding the values of X_r , T_{ad} & t by experiment, the performance of the proposed system can be estimated. The expressions can be simulated for a comparative study with that of the experimental results using standard value for the used parameters enlisted above.

2.1 Observation

The potential analysis for implementing such a polygeneration solar thermal system needs to

- define the aptness & significance of the proposed system for the targeted industrial sector under study.
- evaluate of the process heat demand by temperature range & by the type of process focusing on low to medium ((up to 180) temperature range.

- Technical feasibility of the installation of the proposed system which includes surface area availability, heat demand characteristics, heat demand at the respective temperature, available heat storage system, possibility of further recovery of waste heat etc.
- define industrial process characteristics (i.e. batch or continuous process)
- estimation of processing temperature range
- techno-economical feasibility study including evaluation of energy & investment cost, cost simulation, operation & maintenance, institutional financing, incentive on clean & green energy use, analysis of payback time, internal rate of return, cost per kWh, challenge & completion in the relevant field etc

3.0 Discussion

Performance of the proposed process is regulated by the manner of feed handling in the dryer, temperature sensitiveness of the feed, maximum temperature range & quality of heat. It is very important to note that in practice one must select and specify a drying system which includes pre-drying stages (e.g., mechanical dewatering, evaporation, preconditioning of feed by solids back mixing, dilution or pelletization, and feeding) as well as the post drying stages of cleaning, product collection, partial recirculation of exhausts, cooling of product, coating of product, agglomeration, etc. Economic incentives like low interest rate loans, tax reduction, direct financial support, third party financing can attract investors to popularize such a solar polygeneration drying system. Further organizing of workshop and campaigns for the industrial sectors involved to make them aware of the real cost of heat production, benefits of using appropriate polygeneration solar thermal technology etc are also necessary.

3.1 Conclusion

30% of the industrial process heat is below 100 $^{\circ}C$ and 27% between 100 $^{\circ}C$ and 400 $^{\circ}C$ This implies that industrial sectors in the chemical, paper, food processing, textile sectors, etc, the possible areas of application including different processes like drying, washing**,** process steam production, chemical reaction, boiling, etc need the process heat in the temperature range achievable from such a polygeneration solar thermal system.

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